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Aircraft Structures Technical Memorandum 570

USE OF PHOTOGRAMMETRY TO MEASURE A PLATE VIBRATION MODE

by

P.A. Farrell, T.G. Ryall and Betty Emslie

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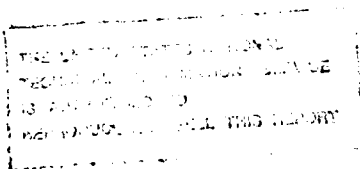
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SUMMARY

Photogrammetry is used to measure the coordinates of points on the surface of three-dimensional bodies. The present report describes a preliminary experiment in the use of photogrammetry to determine the vibration mode shape of a structure. Synchronised stroboscopic illumination was used to "freeze" the motion of a plate undergoing sinusoidal excitation at a natural frequency whilst a number of photographs were taken at different phase angles through the cycle of oscillation. The motion of the plate was non-sinusoidal due to the presence of non-linearities so a weighted least squares process was used to determine the required mode shape. This mode shape is compared with that measured by a more traditional method.



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1 INTRODUCTION

Photogrammetry is a procedure which is used to measure, non-intrusively, the three-dimensional coordinates of points on the surface of a body. In this technique a number of photographs are taken of the body from different locations and the resulting photographs analysed to give the required results. It is not necessary to know the precise location of the camera for each photograph as the solution process provides this. A vibrating structure, "frozen" by a synchronised stroboscope, could be measured in the same way. This report describes the determination of a normal mode of vibration of a plate using photogrammetry, and compares the result with that measured using a more traditional method.

2 TEST SPECIMEN

The test specimen consisted of a rectangular cantilever steel plate of dimensions 1022 mm by 902 mm by 3 mm, with the shorter side being built in. It is shown schematically in Figure 1. A previous report (Reference 1) describes the design of this test specimen and the theoretical determination of its natural frequencies and mode shapes. The mode of interest was the fourth normal mode whose natural frequency was measured to be 27.2 Hz. The motion of the plate in this mode suffered from severe harmonic distortion, with the main contamination being at twice frequency. As measured with an accelerometer placed at a point of maximum displacement in the mode, the first harmonic had a magnitude of some 12 % of the fundamental. At points of lower amplitude, the fundamental and first harmonic were of comparable magnitude. Since the contamination resulted from the presence of an even harmonic, the motion of the plate was not "equal sided" in the mode; i.e. the static position of the plate was not the mean of the positive and negative extremes of the motion.

A computer-generated sine wave of the correct frequency was amplified and used to drive an electromagnetic shaker attached to the plate at the location shown in Figure 2. The computer simultaneously generated another sine signal of the same frequency but at a different phase to the excitation signal. This was used to trigger the stroboscope.

3 PHOTOGRAMMETRIC MEASUREMENTS

Photogrammetry is essentially the use of the principles of geometrical optics to convert perspective information, from a number of photographs of an object taken from different aspects, into three-dimensional information. Using photographs from a camera which has some of the characteristics of a pin-hole camera, the ray paths are reconstructed to the photographed object. Fiducial marks are recorded on the film so that film distortion (stretching or contraction after exposure) can be compensated. Similarly aberration due to the lens is eliminated. Generally photogrammetry is used to measure static objects but in the present test a stroboscope was used to "freeze" a vibrating plate and photogrammetry used to measure the displaced shape.

Reflective targets were attached to the plate at the locations shown in Figure 2. A further six targets were attached to non-vibrating structures near the plate such that when photographs were taken of the oscillating plate, a number of these stationary targets also showed in each photograph. Photographs were taken from five positions around the plate, each approximately equidistant from the centre of the plate and equiangular about the plate, in a plane parallel to the plate but about two metres above it.

Eight photographs were taken from each location, with the phase between the stroboscope trigger and the excitation being increased progressively by 45 degrees for each photograph. The phase between the stroboscope flash and the excitation for the first photograph (the phase datum) was set to correspond approximately to an extremum of the modal motion.

Dr.M.Shortis of the Surveying Department, Melbourne University conducted the photographic aspects of the experiment and also was responsible for reducing the photographic data to give the displacements of the targets on the vibrating plate for each stroboscopic phase angle. The analytical techniques for converting the measured locations of points on planar photographs into three dimensional coordinates is beyond the scope of this paper but is described in Reference 2.

The process of obtaining the raw data from the photographs is manual and very time-consuming, so for the present test not all the phase angles were utilised. Data were provided for the following phase angles: 0, 45, 90, 135, 180 and 270 degrees. The photogrammetry procedure provides an estimate of the error with the results for each phase and the least squares analytical technique used to determine the mode shape uses this error as a weighting.

3.1 Determination Of The Mode Shape

If the motion of the plate were truly sinusoidal and if the displacements were determined without error, then the mode shape could be obtained from the displacements at just three phases; but neither of these conditions is met. The plate, having non-linear stiffness, responds to sinusoidal excitation with a response that is the sum of a number of harmonics. An examination of the signal from a monitoring accelerometer on the plate led to the motion of the i 'th target being expressed as

$$w_i(t) = a_i + b_i \sin(\omega t) + c_i \cos(\omega t) + d_i \sin(2\omega t) + e_i \cos(2\omega t) \quad (1)$$

The five coefficients a_i , b_i , c_i , d_i and e_i may then be determined by a weighted least squares fit of this function to the displacements measured at the six phase angles (ωt) listed above. The least squares error, E , to be minimised is

$$E = \sum_{i=1}^n \frac{(w_i^* - w_i)^2}{\sigma_i^2} \quad (2)$$

where w_i^* is the measured displacement at the i 'th target

w_i is the calculated displacement (from Equation 1)

σ_i is the standard deviation of the relevant measurement error

and n is the number of targets.

Minimising E with respect to the five unknown coefficients (a_i , b_i , c_i , d_i and e_i) leads to five simultaneous equations which are then solved for these coefficients. This procedure is repeated for each of the other targets to give the spatial distribution of the motion.

Figure 3 shows a plot of b against c for each target. A normal mode is mono-phase which means that these plotted points should be colinear; however the slight scatter shows that the values are affected by noise (measurement noise and modelling error). The required mode is thus given by the values of b and c which lie on a line of "best fit" to these points. Note that both b and c have errors so that the usual least squares process in which the independent variable is assumed to have no errors, is inappropriate in this case. Also the datum phase angle (zero degrees) is set only by eye so the mode shape should be independent of this, i.e. the line of best fit should be independent of any rotation of the axes in Figure 3.

This leads to the least squares error, F , being expressed as

$$F = \sum_{i=1}^n [c_i \sin \theta - b_i \cos \theta]^2 \quad (3)$$

where n is the number of targets on the plate. The value of θ which minimises F is then given by

$$\tan(2\theta) = \frac{2\sum b_i c_i}{\sum c_i^2 - \sum b_i^2} \quad (4)$$

and the required modal amplitude, v_i , at the i 'th target is given by

$$v_i = c_i \cos\theta + b_i \sin\theta \quad (5)$$

3.2 Interpolation

The values of v_i provide an estimate of the mode shape sampled at the target locations whose x, y coordinates (see Figure 1) are also produced by the photogrammetry procedure. An interpolation scheme must be implemented to provide the modal displacements elsewhere on the plate. As shown in Reference 1, two sets of beam functions, one for each of the principal directions, with the appropriate boundary conditions may be used for the bivariate interpolation/extrapolation. The form of these orthogonal functions is given in Reference 1. Using this scheme the modal displacements were interpolated to sufficient other locations on the plate to produce a contour plot which, following scaling to give a unit RMS value, is shown in Figure 4.

4 MEASUREMENTS USING AN ACCELEROMETER

To provide a comparison with the mode shape determined using photogrammetry, the mode shape was also measured using a more traditional method. In this latter method an accelerometer was attached to the plate near each target location in turn, and the response of the plate measured. A digital Frequency Response Analyser was used to resolve the motion into its various sinusoidal components, and the mode shape was determined from the component at the same frequency as the excitation. The locations at which the mode shape was measured with the accelerometer were not identical to those used in the photogrammetry procedure (the presence of the target precluded the attachment of the accelerometer to the same position) so the two mode shapes were compared by interpolating them to the same network of points used for the generation of contour plots. Again, the beam functions described in Reference 1 were used for the interpolation and the resulting contour plot, following scaling to give an RMS value of unity, is shown in Figure 5.

5 DISCUSSION

The method used at Melbourne University to extract the primary data from the photographs is very time consuming so the displacements for two of the eight photographed phase angles (namely 225 and 315 degrees) were not determined. Consequently, if an analytical procedure is to be used to minimise the effects of noise, at most five coefficients can be used in the functional description of the displacement (Equation 1). If the data for more phases were available, an expansion for w could be used containing more terms than those in Equation 1. Conversely the number of coefficients could be kept at five but the greater redundancy of more phases should improve the "fit".

A quantitative measure of the colinearity of the points plotted in Figure 3 is given by R , where

$$R = \sqrt{\frac{\sum (c_i \sin \theta - b_i \cos \theta)^2}{\sum (c_i \cos \theta + b_i \sin \theta)^2}} \quad (6)$$

and θ is given by Equation 4. In the present case R has the value 0.075 which is considered quite acceptable.

A comparison of Figures 4 and 5 shows quite good agreement between the mode shapes measured by the two techniques. Both figures show that the contour pattern is not symmetric about the x axis (see Figure 1 for the axis system) and that the distortion is similar in each figure. The region between the clamped (left) edge and the centre of the plate is one of low amplitude and low slope, so that very small changes in displacement result in large changes to the contours here. A quantitative measure of the agreement between the two figures is the correlation coefficient evaluated at the points used for the contour generation. This coefficient has the value 0.9985 which demonstrates that the agreement between the two figures is quite good.

6 CONCLUSION

Photogrammetry was used to measure a normal mode of an oscillating cantilever plate. Because the motion of the plate suffered from harmonic distortion the required mode shape was determined by a weighted least squares technique. The mode shape determined in this way agreed well with that obtained by a more traditional method, namely direct measurement with a travelling accelerometer.

7 REFERENCES

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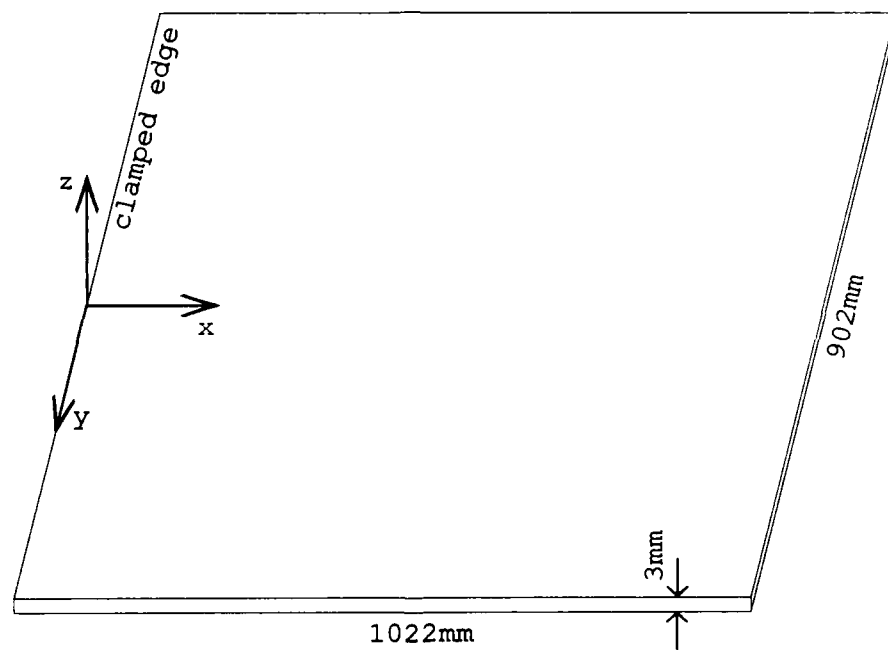


Figure 1. Rectangular cantilever plate, showing axis system

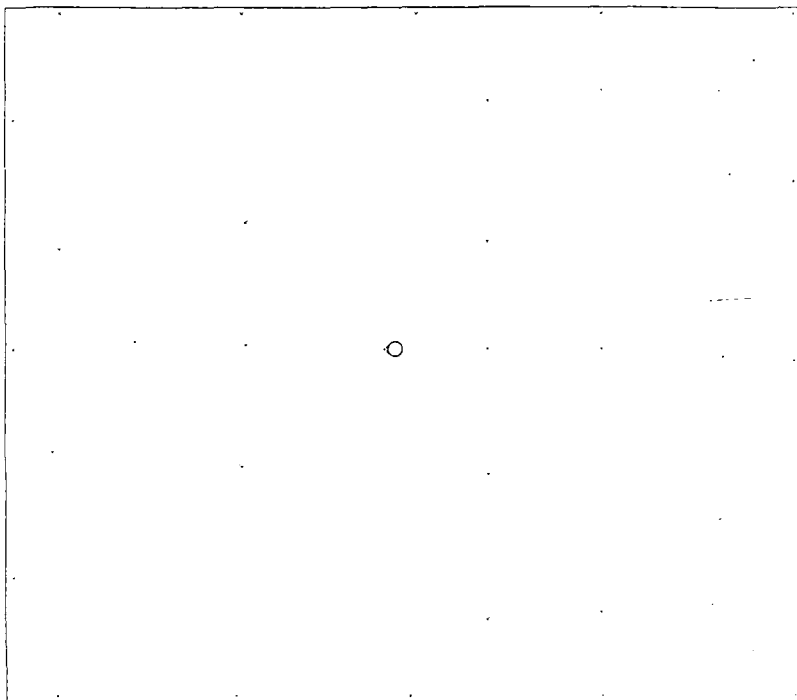


Figure 2. Location of reflective targets, X, and shaker, O.

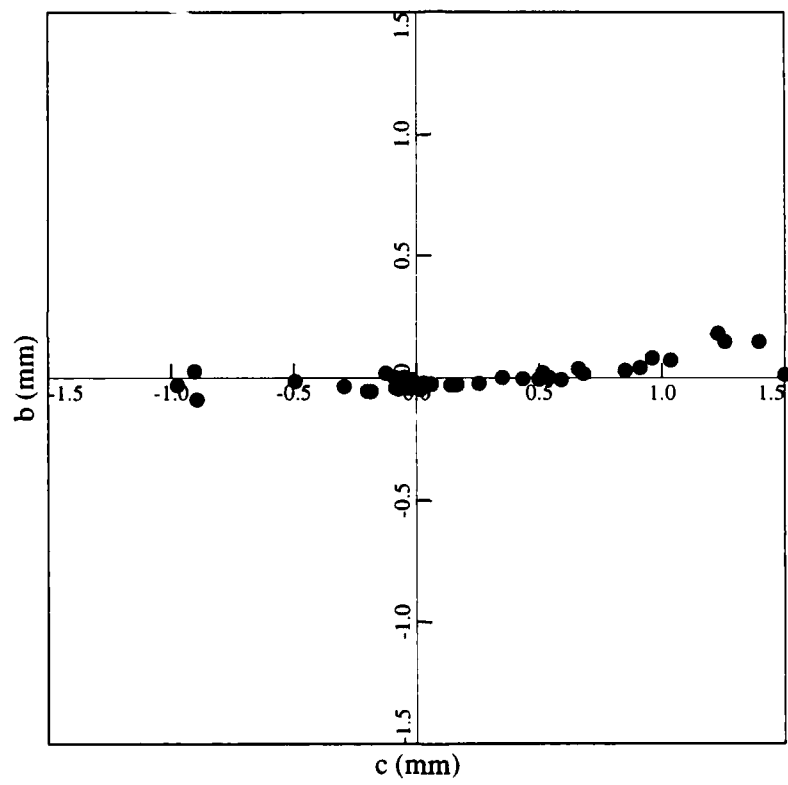


Figure 3. Plot of b against c for all targets

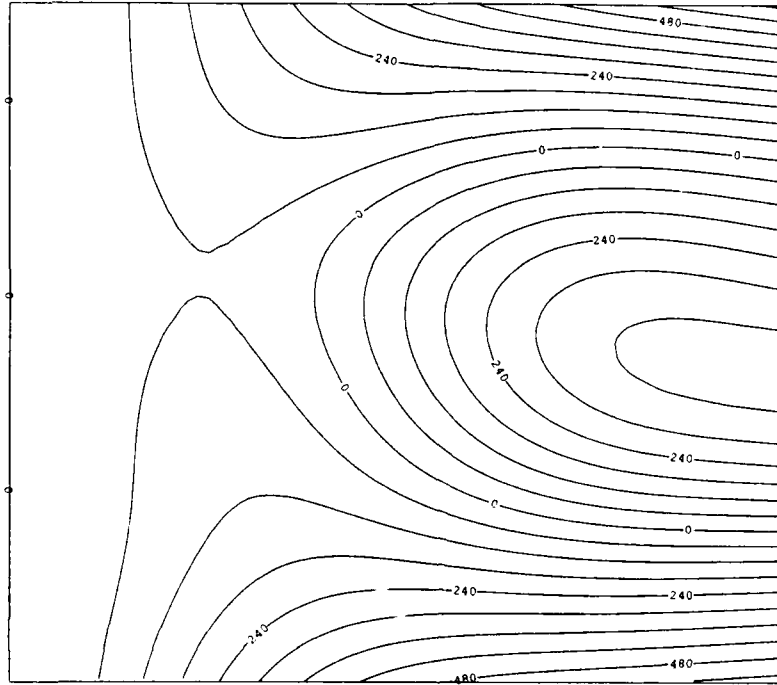


Figure 4. Contours depicting mode shape measured by photogrammetry

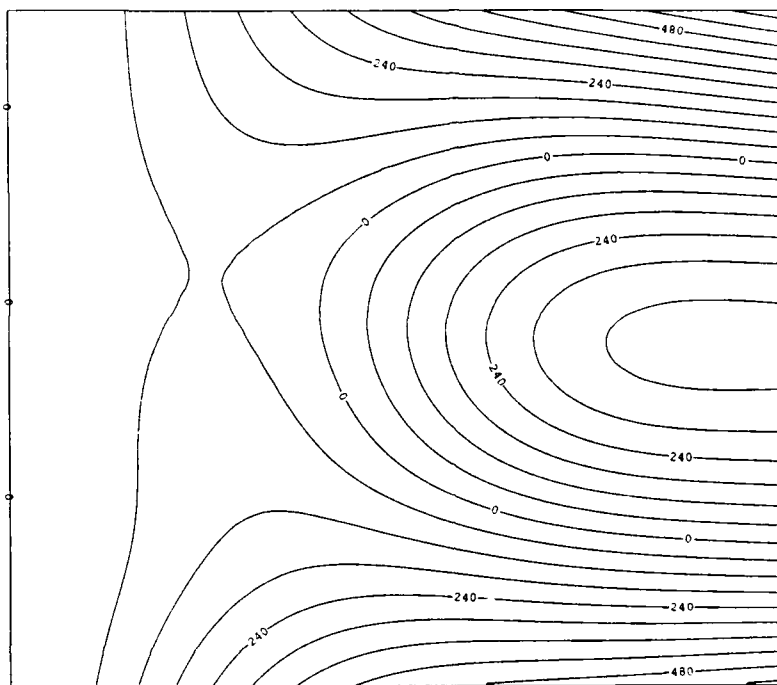


Figure 5. Contours depicting mode shape measured with accelerometer

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